RFID-Grids for deformation sensing

Stefano Caizzone, Gaetano Marrocco, *IEEE Member*

***Abstract*—This paper explores the possibility to monitor structural deformations by means of grids of antennas. Deformations, occurring in engineering structures due to unexpected loading conditions and to obsolescence, may lead to potentially dangerous events, especially in critical environments such as aerospace platforms or civil infrastructures.**

By engineering the electromagnetic interaction among the elements of a grid of UHF Radiofrequency Identification (RFID) tags, it is possible to extract various measurable indicators useful to track the local as well the overall deformation of the body on which the antennas are attached on, and hence to monitor the "health" of sensitive structures.

***Index Terms*—RFID, Antenna coupling, Sensor, Grid, Deformation, Structural Health Monitoring**

I. INTRODUCTION

The design of engineering structures, from bridges to buildings [1] to airplanes and satellites, is carried on taking into account the mechanical properties of materials and the environmental conditions that the object is going to experiment during its life span. In order to ensure the correct operation of the designed structure, as well as to take into account unexpected events, it is beneficial to check its actual "structural health" at regular time intervals, with the purpose to spot possible damages at an early stage, to avoid more dangerous problems.

The monitoring techniques change widely according to the kind of structure under test: in most cases, however, visual inspection is the only check that is periodically performed over the structure, or even on demand in case some potential damage has been envisaged. It would therefore be foreseen an in-situ continuous monitoring of safety-critical structures, such as for instance airplanes or bridges, in order to provide real-time useful information about the status of the structure and to possibly prevent disastrous situations.

Several methods are currently available to monitor strains in engineering structures [2], [3], [4]: most of them involve the use of optical fibers which will detect deformation through changes in the optical signal, ultrasonic waves whose propagation characteristics will change in case of structural modifications, or current probes which have to stay close to the structure in order for the eddy currents to detect fractures or deformations. However, affordable solutions for a true continuously-monitoring should involve wireless systems because of the difficulty to install additional wires onboard and for the resulting extra-costs.

Very recently, some preliminary ideas have been presented about how to use planar antennas, loaded by passive RFID (Radio Frequency IDentification) transponder, as deformation sensors [5], [6], [7]. Their physical rationale is the different behavior that a single antenna (a dipole, a meander-line antenna or a patch) exhibits when its structure is stretched, i.e. its electrical length is subjected to change. Such a modification also produces a variation in the antenna response, remotely detectable. These kinds of devices, acting at a same time as radio-transponders and sensors, are promising and allow to monitor a given point in the structure under observation. The development of an alignment of such antennas would enable to monitor wider areas.

S. Caizzone is with the Institute of Communications and Navigation, German Aerospace Center (DLR), Oberpfaffenhofen, Germany, as well as with the DISP, University of Rome, Tor vergata, Italy. E-mail: stefano.caizzone@dlr.de.

G. Marrocco is with the DISP, University of Rome, Tor Vergata, Italy. E-mail: marrocco@disp.uniroma2.it.

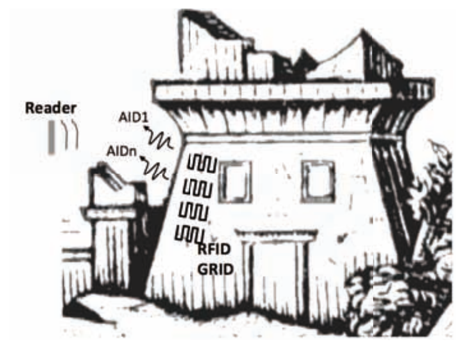


Figure 1. Pictorial representation of a RFID-GRID system to sense surface deformations of hystorical monuments

In the present paper the issue of using RFID antennas as deformation sensors is addressed in a more general way, by introducing a passive distributed wireless monitoring technique.

The envisaged system is thus composed by a grid of RFID antennas (tags) properly placed over the structure (Fig.1) and by a remote reader device, which wirelessly powers the sensing antennas and collects their responses produced by a modulated backscattering. The processing of the retrieved signals from each antenna of the grid will provide an aggregated information about the deformation of the grid itself, which if compared with a reference condition, will yield the displacement that the structure has undergone.

The proposed technique has the advantage over other sensing mechanisms of requiring neither costly dedicated sensors and specific communication devices, nor additional wires to be installed in the structure, and hence it is particular attractive for aeronautical environments.

The paper describes both mechanical and electromagnetic models of strain sensing with some preliminary laboratory experimentations.

II. RATIONALE OF DEFORMATION SENSING BY RFID GRIDS

It is well known that the input impedance of antennas placed at a close distance suffers from mutual coupling effects.

978-1-4673-0328-6/12/$31.00 ©2012 IEEE

For instance the mutual resistance and reactance of a couplet of half-wavelength parallel dipoles are oscillating functions [8] dumping to zero as the inter-antenna distance increases. However, if the distance is less than about $\lambda/2$, the relationship between mutual impedance and distance is monotonic. Hence a remote estimation of the variation of coupling could provide the basis for surface deformation, provided that a grid of strongly coupled antennas is considered all over the interesting part of the infrastructure.

The key-point is therefore the wireless estimation of changes in inter-antenna coupling within an alignment of RFID tags. A possible way is given by the recent theory of RFID grids [9], [10]. A grid of RFID tags can be thought of as a close displacement of antennas, which will be considered as an electromagnetic interconnected system having specific properties.

Physical information about the Grid, and about its interaction with the structure on which it is placed on, can be extracted from the *Analog IDentifier* AID_n of the nth port, independently on the reading modalities. The analog identifier has been defined in [9] as a function of the turn-on power P_n^{to} of the nth port, e.g. the minimum power driving the reader's antenna for which the *n*th port starts responding, and of the backscattered power $P_{R \quad Tn}$ emerging from the grid and measured at the same turn-on power, when the *n*th chip is performing impedance modulation, and afterward collected by the reader. For a typical ASK modulation scheme, the analog identifier may be written in a very compact form

$$AID_n \quad \frac{p_n}{\sqrt{P_{R-\,Tn}\, P_n^{to}}} \quad R_{C,n}|Y_{G,nn}| \tag{1}$$

where $Y_{G,nn}$ are the diagonal entries of the admittance matrix $\mathbf{Y_G} = (\mathbf{Z}_C + \mathbf{Z})^{-1}$ of the grid, being $\mathbf{Z}$ the impedance matrix referred to the RFID microchips' connections, and $\mathbf{Z}_C$ a diagonal matrix containing the equivalent impedances $\{Z_{C,n} = R_{C,n} + jX_{C,n}\}$ of the microchips; p_n is the sensitivity of the microchip at the nth port, and the proportionality operator accounts for the reader's front-end and the modulation scheme and may be removed by calibration.

The left-hand side of the Analog Identifier definition is linked to parameters achievable through measurements with commercial readers and therefore can be used to practically retrieve the AID from measurements. Moreover the right-hand side of (1) relates the AID_n to the change in the impedance matrix of the system and indirectly to the geometrical distribution of antennas.

The set of $\{\text{AID}_n\}_n = 1..N$ together with the digital identifiers $\{\text{ID}_n\}$ of the microchips gives the *grid's fingerprint* which is a data structure that permits to discriminate the response of each tag/port and hence to naturally trace the local variation of the inter-port relationships and therefore of the deformation experienced by the grid. It is also worth recalling that the AIDs are independent on the reader-grid mutual orientation and distance and even on the nearby environment. Hence, this kind of data promises to produce a reliable metric to apply in successive observation of the structure without the need to exactly replicate the same measuring conditions. Other sensing metrics are moreover possible, such as the turn-on power and the backscattered power themselves. They are expected to be more sensitive to the change of mutual coupling because of the additional dependance on the antennas' gain. The measurement of these indicators is however position-sensitive and hence they are suited just to fixed readers. The following discussion will be focused on the only AID metrics, while some example of dependance of the turn-on/backscattered power versus the deformation of the grid will be presented in the experimental Section.

III. Parametrization of deformations

Before going into the data processing procedure to be applied to the RFID Grid fingerprint and show some examples, it is worth introducing a few basic concepts from [11] about parametrization of structures deformation.

A. Displacements and strain

The shift of each point of the body is described by a *displacement vector*:

$$\bar{d} = u(x,y,z)\hat{i} + v(x,y,z)\hat{j} + w(x,y,z)\hat{k} \tag{2}$$

where $\hat{i}, \hat{j}, \hat{k}$ are respectively the unitary vectors of the x,y,z axis and u, v, w are the displacements along each axis. Therefore, a point $P(x,y,z)$ will become, after the stress is applied, a new point $P'(x+u, y+v, z+w)$. The displacement can be seen as the presence of a strain in the structure caused by the stress.

Normal strains are of particular interest and are defined as the incremental change in length divided by the original length, i.e.

$$_x = \frac{dx}{dx} = \frac{u}{x} \tag{3}$$

B. A Canonical deformation model

The simplest deformation is such that all the points of the body are subject to the same constant strain. In this case, assuming a uni-dimensional stress along the *x*-axis, segments of the same length in the unstressed body will be therefore transformed in equally scaled segments in the stressed object (see Fig.2). In formulas:

$$u = b_0 x + b_1 y \tag{4}$$

with $_x = \frac{\delta u}{\delta x} = b_0$. For simplicity, the tensile strain (b_1) is set to 0. This kind of deformation is representative of dilatations/compressions in an unbounded body, in which the strain is constant in all points. This model is moreover suited to application to linear elastic fracture mechanics (LEFM) [12], such as the analysis of fatigue crack growth for aeronautical structures, where the materials are mainly aluminum alloys.

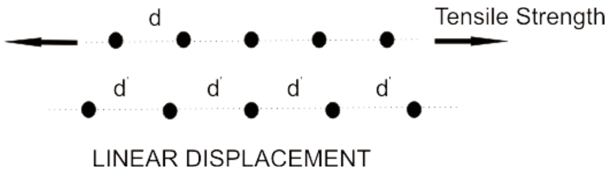


Figure 2. Deformation experienced by an alignment of points through a linear displacement

IV. Grid Fingerprint Processing

The deformation sensing through the RFID-grid effect is basically an inverse problem relating the measured variation of the analog identifiers to the unknown change of inter-element spacing.

The measured data have to be processed in order to provide a relationship with the deformation suffered by the structure in terms of displacement $\overline{d}$ or strain ϵ. A possible pictorial representation of the evolution of the grid fingerprint is the histogram pattern at fixed frequency, as shown in Fig.3: it provides a visual relationship between the change in the geometrical position of the tags and the corresponding modification of each AID_n as a function of the *grid strain*, defined as the incremental change in the length of the whole grid.

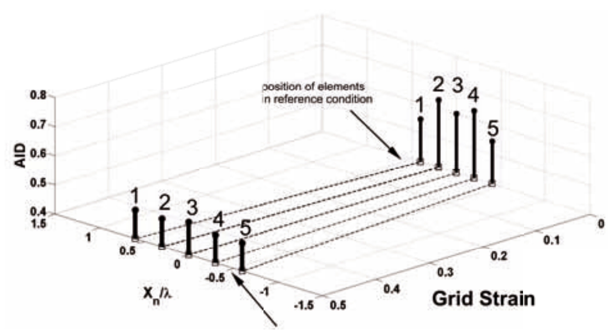


Figure 3. Histogram representation of the grid fingerprint profile as related to the overall strain and to the position of the sensing tags over the surface.

The *sensitivity* of the RFID GRID, when considered as a deformation sensor, can be defined as the ratio between the variation in the measured AID_n and the variation in the strain, e.g. the slope of the curve $AID_n(\epsilon)$ computed as $S_n^{AID} = dAID_n/d\epsilon$. It depends on the particular deformation mechanism and hence will be calculated for every case .

V. Numerical Experimentations

Some numerical examples are here presented with the purpose to investigate the achievable response of the system to the uni-dimensional deformations previously described, as well as to understand the role of the number of elements of the grid and of the inter-element spacing.

To provide general results, no realistic tag geometry has been here considered. The impedance matrix of the grid is hence artificially filled starting from the theory of coupled dipoles. The diagonal impedances Z_{nn} are approximated by the input impedance Z_S of the antenna in standalone configuration [8], so that the antenna length is half a wavelength at central frequency f_0, while the mutual impedances for inter-dipoles spacing d_{mn}, e.g. $Z(d_{mn})$, are calculated through the frequency-domain formulas in [8] and [13] which consider just two dipoles at a time, so neglecting the coupling mechanism beyond the first order. It is worth noticing that dipole-like tags are obviously not suited to metallic platforms (like airplanes) but they could be interesting to understand potentialities and limitations of the method and also for real world application to civil buildings.

The microchips connected to the antennas are assumed to be matched to input impedance of the standalone dipole ($Z_{C,n} = Z_s^*(\lambda_0) = 73 - j43.5$). There are therefore all the data ($[\mathbf{Z} + \mathbf{Z}_C]$ matrix) required, from (1), to calculate the synthetic AID versus the dipole-to-dipole spacing.

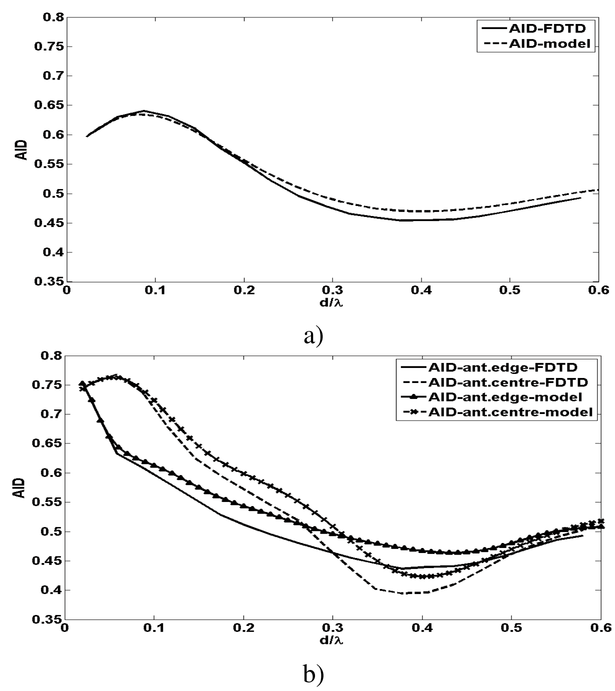


Figure 4. AID vs mutual distance of $\lambda/2$ tags in *a)* 1x2 grid and *b)* 1x5 grid, as predicted by the simplified theoretical model assuming only interactions between couplets of dipoles, and the numerical analysis by FDTD method.

Although this model is rather rough, it is nevertheless able to provide a reasonable, at least qualitative, agreement with a fullwave model based on FDTD simulations of dipoles, as shown in Fig.4 for the cases of 2- and 5-elements equally spaced grids, on varying the inter-element distance. It it possible to observe the presence of a "linearity zone" in the AID for $0.1\lambda_0 < d < 0.4\lambda_0$, wherein all the the curves are monotonic and can be approximated by straight lines. This would enable a non-ambiguous solution for the inverse problem relating the measured variation of the analog identifier to the change of inter-element spacing. This range of distances will hence be analyzed in more detail in the next examples where tags will be often set $0.2\lambda_0$ apart in the reference condition (unstressed state), so that both for a moderate reduction and for a moderate increase in the mutual distance of antennas, AID_n would still remain in this monotonic zone.

A. Linear deformation with constant strain

It is here considered a 1D-RFID Grid of 5 dipoles positioned along the x-axis, at a reference mutual distance between

neighboring antennas equal to $d_0 = 0.2\lambda_0$ for a total length of 0.8λ. Just to fix the ideas, we can assume that $\lambda_0 = 0.345m$ corresponding to the central frequency $f_0 = 870$MHz of the European UHF-RFID band. The grid undergoes a linear deformation due to a constant strain, thus being compressed or elongated along the x-axis. Fig.5 shows the fingerprint histogram at fixed central frequency f_0 (as introduced in Fig.3), e.g. the snapshots of the $\{\text{AID}_n\}$ and of the tags' positions along with the progression of the elongation (grid strain). The curves on the left side-wall of the graph help summarizing the variation of the AIDs between one position and the other. Beside the changes of the bars' value, it is clearly visible the variation of the whole fingerprint profiles. The summarizing lines show a quasi-linear behavior of each AID_n with lower values as elongation occurs and higher values when the strain causes a compression. It is also interesting to point out that, apart from the AID of tags which have suffered a displacement, also the AID of the central antenna ($n = 3$), which remains fixed in the same position for every strain, changes as well, since it nevertheless experiences an increased/decreased mutual distance from the other antennas. The estimated sensitivities in the tracking of the deformation are S_1=17.5% and S_3=29.5% when observing the response of edge and central tags, respectively. This means that a 3% variation of the measured AID_3 will indicate a strain of 0.1, e.g. a variation of mutual distance between antennas of around 0.02λ(=0.7cm at 870 MHz).

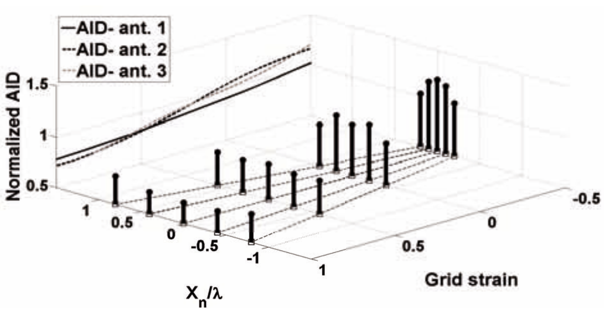


Figure 5. 5-tags RFID-Grid under constant strain (linear deformation)

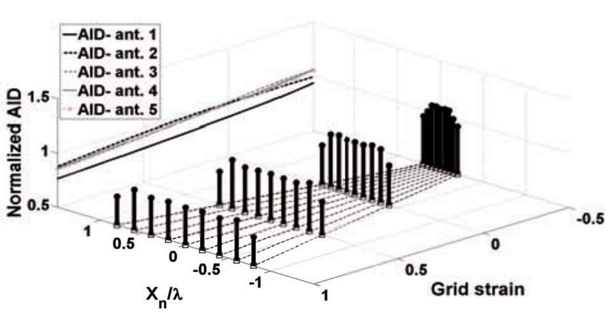
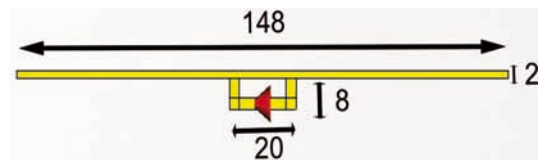


Figure 6. 9-tags RFID-Grid in the same footprint of the grid of fig. 5

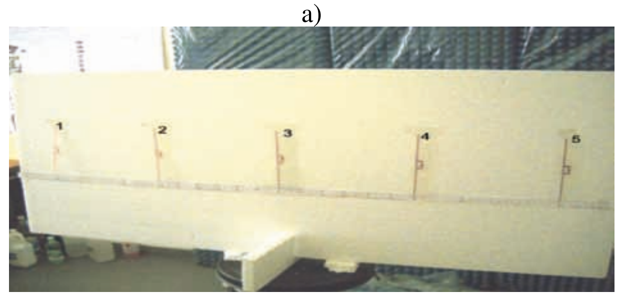
Finally, it is interesting to show what happens when a larger number of tags (say $N = 9$ instead of $N = 5$) are packed in the same 0.8λ surface length, therefore with an initial halved inter-antenna spacing (0.1λ instead of 0.2λ). The corresponding fingerprint profile in Fig.6 has to be compared with Fig.5 for the 5-element grid. It is apparent that the AID_n variations are now much more modest than in the previous case, both in terms of fingerprint profile and values of each AID_n versus strain. In particular the new sensitivities are: $S'_1 = 12.5\%$ and $S'_3 = 12.1\%$. This is because for a same overall strain, the variation of the position of each tag is smaller than in the case of less elements. So in principle there is no particular advantage in increasing the density of tags inside the grid since better sensing may be achieved by using a small number of tags.

VI. Laboratory Experimentation

In order to verify the proposed idea with real antennas, a first example of RFID grid composed of 5 T-match dipole-like tags has been fabricated and measured (Fig. 7). The grid lays over a foam-like substrate. The reader is a Thingmagic M5E device connected to a broad band PIFA antenna and placed in broadside orientation with respect to the grid at distance L=100 cm from it.



a)



b)

Figure 7. a) a T-match dipole tag; B) 5-elements grid laying over a foam panel. The reader's antenna is placed in front of the grid at a distance L=100 cm

The position of the tags inside the grid is manually changed in order to simulate a linear displacement (compression and elongation). The initial condition (zero strain) is that for inter-tag distance d_m=7 cm (corresponding to 0.2λ at 870MHz).

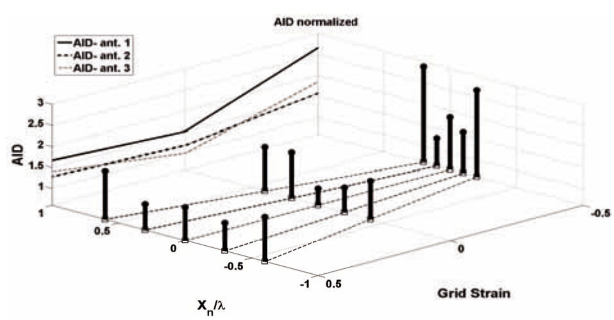


Figure 8. the AID values obtained at 870MHz from the measurement of the grid of UHF dipole-like antennas. AIDs are normalized to the value of the central antenna (n=3) in the position corresponding to null strain.

For each set of positions the reader measures the corresponding turn-on power and the backscattered power of all the tags and finally the AID identifiers are calculated by post-processing according to equation (1). The obtained AID profiles at 870MHz, normalized to the value of the central tag for the initial state with null strain, are shown in Fig. 8.Measurements show a decreasing profile, as expected from the previous theoretical results. Some disagreements may be visible in the response of the outer antennas, probably due to the edge effects of an array**.** Such effects alter the gain of the outer antennas so that there can be substantial differences in the power impinging on the different ports, hence resulting in possibly triggered non linearities in the chips. For the sake of completeness, also the measured turn-on power and backscattered power versus the grid strain are shown in Fig.9 and Fig.10. These indicators show an higher sensitivity to the strain than that of the AID, with significant variations throughout the deformation range with sensitivity $S_3^{turn-on}$ =7.3dB and S_3^{bs} =9.7dB for 100% strain, concerning the turn-on power and backscattered power of the central antenna. However, they are not invariant with the measurement setup [10] and therefore they need fixed measurement conditions.

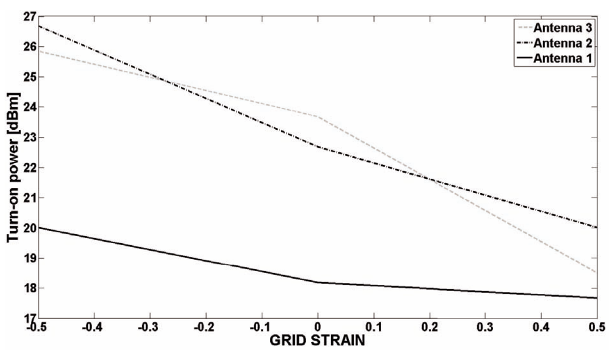


Figure 9. Turn-on powers of some elements of the 5-tags versus the grid deformation measured at a reader-grid distance L= 100cm

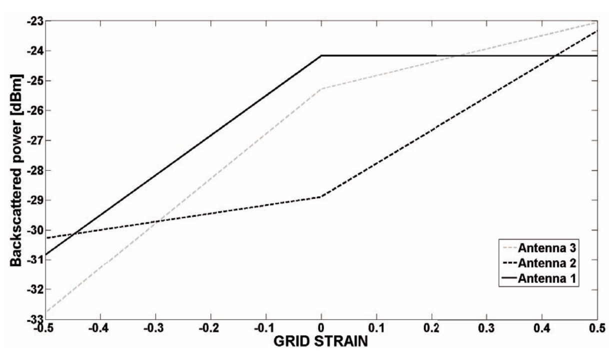


Figure 10. Backscattered powers emitted by some tags of the grid as measured by the reader, through RSSI values

VII. Conclusions

The described models and examples seem to demonstrate that the processing of the RFID grids' fingerprint permits in principle to produce an estimation about the overall amount of surface deformation as well as to provide a local representation of the displacement. Having chosen the inter-tag distance, the overall sensitivity of the considered measurement platform does not appear strongly dependent on the number of tags. Instead, the sensitivity becomes weaker when the inter-antenna spacing reduces. Therefore, for a required area of surface under observation, it is possible to find an optimum spacing of the grid such to maximize the sensitivity and to preserve monotonic responses of the tags within the whole expected deformation range. Moreover, the sensitivity of the grid to the strain is expected to be more remarkable if deformable (read elastic) antennas are used, such as meander line dipoles made by super-elastic conducting alloys [14] or inkjet printed antennas over elastic substrates.

The paper has mainly focused on position-independent indicators, such as the AID and their derivatives, however experimentations have shown that pure power (turn-on and backscattered) metrics are able to provide even higher sensitivity and hence they could be fully considered in case of fixed interrogations.Also frequency responses of the various indicators might be taken into account for a richer data retrieval process. Some results will be shown during the conference.Finally, this kind of sensing platform could generate a large amount of data and therefore ad-hoc processing algorithms need to be developed to achieve a true imaging of the deforming surface, fully accounting for the interaction with the nearby environment and the inherent multi-physics (mechanical and electromagnetic) nature of the problem.

References

[1] C. Boller, N. Meyendorf, "State of the art in SHM for Aeronautics", *Proc. of the International Symposium on NDT in Aerospace, 2008*

[2] Diamanti, Soutis, "SHM techniques for aircraft composite structures", *Progress in Aerospace Sciences 2010*

[3] G.Mook, F. Michel, J. Simonin, "Electromagnetic Imaging using probe arrays", *Proc. of the 10th International Conference for Non-Destructive Testing,* Ljubljana, Slovenia, Sept. 2009, pp.349-366.

[4] T.Kundu, "Advanced ultrasonic methods for material and structure Inspection", *Wiley, 2010*

[5] A.Daliri et al., "Circular microstrip patch antenna strain sensor for wireless structural health monitoring", *Proc. of the World Congress on Engineering 2010,* London, U.K. Vol.2

[6] C. Occhiuzzi, C. Paggi, G. Marrocco, "Passive RFID Strain-Sensor based on Meander-Line Antennas", *in press on IEEE Trans. Antennas and Propagat. 2011*

[7] S. Merilampi et al., "Embedded wireless strain sensors based on printed RFID tag", *Sensor Review,* Vol.31, N.1, pp. 32-40, 2011

[8] C. A. Balanis, "Antenna theory: analysis and design", *J. Wiley and Sons, 1997*

[9] G. Marrocco, "RFID Grids: Part I - Electromagnetic Theory", *IEEE Trans. Antennas and Propagat.* Vol.59, N.3, pp. 1019-1026, March 2011

[10] S. Caizzone, G. Marrocco, "RFID Grids: Part II - Experimentations", *IEEE Trans. Antennas and Propagat.* Vol. 59, N.8, pp. 2896-2904, Aug. 2011, "Antenna theory: analysis and design", *J. Wiley and Sons, 1997*

[11] G.W.Housner, T. Vreeland, "The analysis of stress and deformation", *California Institute of Technology Publication, 1965*

[12] R.I.Stephens et al., "Metal Fatigue in engineering", *2nd Edition, Wiley and Sons, 2000*

[13] H. E. King, "Mutual impedance of Unequal length antennas in echelon", *IRE Transactions on Antennas and Propagation,* Vol.5, N.3, pp. 306-313, 1956

[14] H. Funakubo, *"Shape Memory Alloy"*, New York: Gordon and Breach Publishers, 1987